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ADCP observations of the western Adriatic slope current during winter of 2001

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Abstract

Data from an Acoustic Doppler Current Profiler (ADCP) mooring maintained during the winter of 2001 in 57 m of water near Senigallia, Italy are used to describe the winter conditions of the Western Adriatic Current in the northern Adriatic Sea. Wind and water temperature measurements from the Acqua Alta tower in 19 m water depth off Venice and winds from a 4-km resolution reanalysis model, COAMPS™, are used to interpret the ADCP data, especially with respect to currents generated by bora winds. At the ADCP site, mean depth-average current for the winter deployment period was 10.4 cm/s toward 140°, roughly aligned with local bathymetric contours. Both mean currents and fluctuations about the means were highly barotropic during the winter. Southeastward (along-shore), mean currents increased slightly (1.8 cm/s) with depth between 7 and 47 m following a nearly linear trend. Offshore (cross-slope), mean currents only increased (2.0 cm/s) deep in the water column, between 35 and 51 m. Current variability was dominated by four bursts of currents in which flow toward the southeast greatly increased. These bursts followed bora winds, the timing of which was identified by measured winds at the Acqua Alta tower. Depth-averaged, de-tided currents exceeded 30 cm/s during all four events, and reached 45 cm/s during one event. Correlations between these along-shore currents and simulated wind stress from the COAMPS model were calculated over the whole north Adriatic. The cross-covariance between currents and wind stress had a spatial pattern similar to the bora wind itself, reaching maxima along the northern Adriatic coast, off the southern tip of Istria, and near Ilovik Island (14.5°N, 44.4°E). Wind stress in these regions had stronger correlation with currents at the mooring than did wind stress anywhere near the mooring. Bottom water at the mooring was too warm for it to have been North Adriatic Dense Water, except perhaps for a brief pulse of cold water associated with the third current burst on April 1st.

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1. Introduction

The Adriatic Sea is a marginal sea of the Eastern Mediterranean extending southeastward from 46°N to 40°N. It is approximately 780 km long and 120–200 km wide. Its central and southern portions are characterized by two large-scale depressions, the 270 m deep Middle Adriatic Pit (also known as the Jabuka Pit or the Pomo Depression) and the 1200 m deep South Adriatic Pit. These features are separated by the Palagruža Sill. Communication of waters between the Adriatic Sea and the Ionian Sea (and thus the Eastern Mediterranean) occurs through the Strait of Otranto. Cushman-Roisin, Gačić, Poulain, and Artegiani (2001) present a comprehensive review of the physical oceanography of the Adriatic Sea.

The general circulation of the Adriatic is cyclonic with southeastward flows along the western side of the sea and northwestward flows along the eastern side (Orlić, Gačić, & La Violette, 1992). Southwestward flows north of both topographic depressions and near Istria form three embedded cyclonic patterns inside the overall cyclonic circulation (Poulain, 2001). The East Adriatic Current (EAC) brings Levantine Intermediate Water and Ionian Surface Water into the Adriatic. Currents along the western side of the sea export fresh water in the surface layer and dense water below the surface layer to the Ionian Sea (Orlić et al., 1992). In the present paper, this southeastward current as a whole, including both its surface and deeper branches, will be referred to as the West Adriatic Current (WAC) following the definition of Poulain (2001).

The northern Adriatic (Fig. 1) is characterized by depths of a few tens of meters, increasing gradually toward the Middle Adriatic Pit. The western coastline is mostly featureless except for the Po River delta near 45°N. The eastern coastline is irregular, marked by the mountainous Istrian Peninsula and numerous islands and bays. Depths in and around these bays are sometimes greater than 80 m. The bay southeast of Istria, Kvarner Bay, is ~50 m deep and connects to the rest of the northern Adriatic through a 30 km wide passage. The other bays connect to the northern Adriatic and to each other through passages that are much narrower than the Kvarner Bay passage, but are comparable to it in depth.

The WAC is formed in the northern Adriatic. The Po River discharges in winter on average 1500 $m^3\ s^{-1}$ of fresh water (Raicich, 1994). This fresh water flows southeast over the narrow shelf (~20 m deep) along the Italian coast, thus forming the onshore portion of the WAC (Hopkins, Artegiani, Kinder, & Pariante, 1999). The offshore portion of the WAC is formed when southwestward flow, following the 50 m isobath, turns southeast along the western Adriatic slope (Zore-Armanda et al., 1996).

In winter, the northern Adriatic is subject to strong winds, called bora, blowing southwestward from the mountainous eastern coast. Bora winds are typically associated with the extension of the Azores anticyclone over Europe that brings around its eastern border cold and dry Siberian air. The catabatic flow of this air from the Dinaric Alps to the sea produces a violent, gusty wind, whose geometrical details are established by the local orography. The extent of the area affected by bora winds depends on the position of the anticyclone and on the meteorological pattern present over the Balkans. The kind of bora described here usually affects the entire Adriatic Sea and is called bora chiara (clear bora), being associated with dry, cold, clear conditions. This name distinguishes it from bora scura (dark bora), which occurs when strong northwestward winds (sirocco) turn westward in the Gulf of Trieste and off Venice. Dark bora events are almost always associated with clouds, rain, and warmer temperatures. In this paper, we will only discuss clear bora

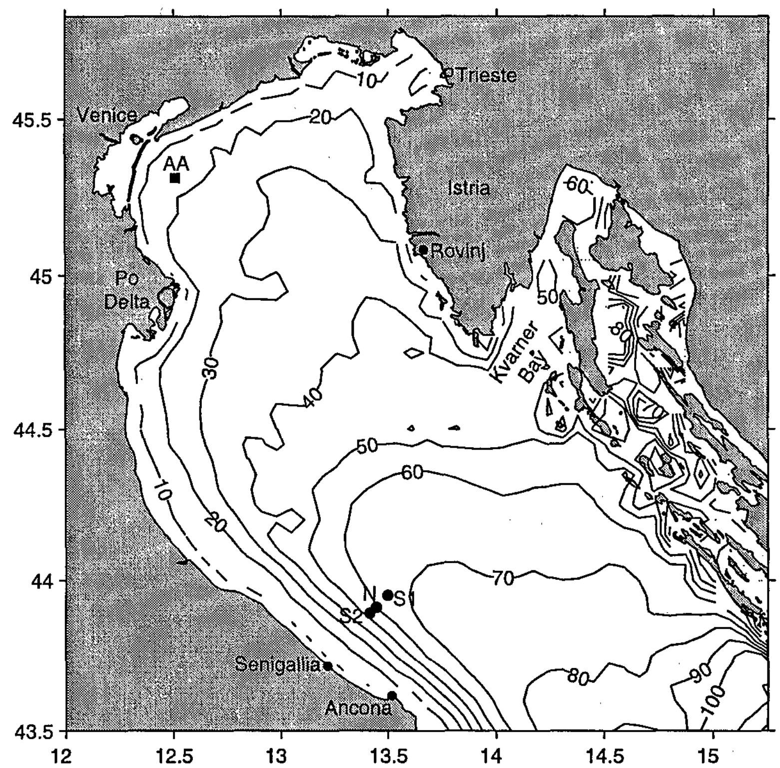

Fig. 1. Locations of ADCPs (S2, N, S1) and the Acqua Alta Tower (AA) in the northern Adriatic Sea. Bathymetric contours are in meters. Vertical and horizontal axes are given in degrees north latitude and east longitude, respectively.

and will refer to them simply as bora. The strong heat flux associated with a bora contributes to the formation of North Adriatic Dense Water (NAdDW). Artegiani and Salusti (1987) observed NAdDW flowing as a thin discontinuous vein along the western Adriatic slope during the winter of 1981. The dynamics of such a vein were explained as a first approximation by the model of Shaw and Csanady (1983), in which dense water is advected along isobaths of a slope.

Bora winds also affect the northern Adriatic by changing its circulation for short periods during and following wind events. Bora winds have strong horizontal shear because of localized blocking by east-coast topography. Zore-Armanda and Gačić (1987) analyzed current meter records in the northern Adriatic under bora conditions and suggested that this wind shear acts on the ocean to form two gyres. In their schema, one cyclonic gyre forms in the far north. South of it, the circulation is anticyclonic as currents flow northeastward from the Po River mouth to the Istrian coast, southeastward along the Istrian coast, and southwestward from Kvarner Bay to the Italian coast northwest of Ancona, Italy. The limited domain model of Kuzmić and Orlić (1987) and the full Adriatic model of Orlić, Kuzmić, and Pasarić (1994) predicted such a double-gyre system during bora conditions, in agreement with the measured currents. Analysis of Coastal Zone Color Scanner images show that during bora events, Po River water can be advected upwind, northeastward toward Istria (Kuzmić, 1991; Sturm, Kuzmić, & Orlić, 1992). Paklar, Isakov, Koračin, Kourafalou, and Orlić (2001) showed that wind stress, surface heat flux, and riverine input were all required in their model to predict accurately an offshore advection of cold Po River water observed by the Advanced Very High Resolution Radiometer satellite during a bora event. Their model shows a strong northern cyclonic gyre, a small anti-cyclonic gyre north of Kvarner Bay, and cyclonic circulation south of Ancona.

Bergamasco, Oguz, and Malanotte-Rizzoli (1999) found in their model that the WAC is intensified during bora events.

In this paper, we examine the winter circulation of the WAC in the northern Adriatic primarily through analysis of mooring data gathered at one site over the winter of 2001. This mooring was deployed on the western Adriatic slope in the outer WAC where the vein of NAdDW had been observed in previous winters.

2. Observations

2.1. Velocity

From January 28 through June 13, 2001, a single Acoustic Doppler Current Profiler (ADCP) mooring (N) was maintained at a depth of 57 m near Senigallia, Italy. During the start of this deployment, two additional ADCPs (S1, S2) were moored on either side of the long-term mooring for two weeks in water depths of 52 and 66 m, respectively. All moorings measured bottom temperature and mooring N also contained a wave/tide gauge that measured bottom pressure. Fig. 1 shows the locations of these moorings. All ADCPs were RD Instruments Workhorse ADCPs operating at 300 KHz. Each one was housed in a trawl-resistant bottom mount known as a Barny, the name being derived from its barnacle-like shape (Perkins, de Strobel, & Gualdesi, 2000). Its design is intended to minimize fishing damage and thus allow for long-term deployments in heavily fished coastal waters.

Instrument setup and subsequent processing resulted in an estimated current error of 1 cm/s. Additional errors may be present in the upper bins during storms due to unresolved surface wave orbital velocities. A few data gaps, concentrated at the surface, occurred occasionally throughout the duration of the records; mooring N had a dropout rate of 13% in its shallowest bin but less than 1% for bins below 15 m. Data gaps at the surface are not uniformly distributed but are concentrated during particular "events" suggesting contamination by storms, possibly through generated bubbles. Surface bins also had higher estimated errors for their good values, reaching 1.6–1.8 cm/s at the shallowest bin of each mooring. Tidal velocity fluctuations were removed from currents at each depth level by a least-squares harmonic fitting algorithm (Foreman, 1977) using the 5 largest constituents at mooring N. At moorings S1 and S2, only the 3 largest constituents were used because of the shortness of the deployments. Table 1 shows more detailed information pertaining to the ADCP moorings. All results presented in this paper are from de-tided data.

Means and standard-deviation ellipses for selected depths for the first portion of data at Site N are shown in Fig. 2. This period extends from the deployment time in late January through April 30. After May 10, the ADCP record is dominated by strong baroclinic inertial oscillations that are probably associated with the seasonal increase in water column stratification. Artegiani et al. (1997a) citing the method of Anati (1977) determined that the ocean season of winter for the Adriatic is from January through April. Therefore, the first interval of data from mooring N will be referred to as the winter period, although almost all of January is absent. The mean depth-averaged current for the winter period was 10.4 cm/s directed toward 140°. As Fig. 2 shows, the mean currents were barotropic to first order, having only small variations with depth. Temporal variability as measured by the standard-deviation ellipses changed little through most of the water column. However, above 10 m it was somewhat stronger and more isotropic, and below 45 m it was slightly weaker. The mean currents exhibited small but detectable trends with depth (Fig. 3). Mean speeds from 15 m through 47 m increased nearly linearly, from 9.8 to 11.0 cm/s, but then decreased below 47 m. From the shallow to the deep bins, the mean currents turned toward the east, the amount of veering increasing with depth. Between 15 and 35 m depth, veering was small, from 143° to 141°. However, between 35 m and the bottom bin at 51 m the direction veered from 141° to 130°.

Fig. 4 shows the observed velocity at three representative depths for the winter period at mooring N. The velocity vectors have been rotated such that 133° is aligned with the negative y-axis, that direction being

Table 1
Description of data collected by the three ADCPs

Site	S2	N	S1
Latitude	43°53.538′	43°54.716′	43°57.039′
Longitude	13°24.919′	13°26.754′	13°29.958′
Offshore distance (km)	25	28	34
Water depth (m)	52.1	57.1	65.5
Start time (UCT)	28 January 01	28 January 01	28 January 01
Stop time (UCT)	10 February 01	13 June 01	10 February 01
Δt (min)	5	15	5
Δz (m)	2	2	2
Avg. min. depth (m)	5.9	6.6	7.3
Avg. max depth (m)	45.9	50.6	59.3
% Data dropout	5.2	1.5	3.1
Avg. error (cm/s)	1.1	1.1	1.1
M_2 semi-major axis (cm/s)	7.6	7.3	8.0
S_2 semi-major axis (cm/s)	4.9	4.6	4.5
K_1 semi-major axis (cm/s)	5.5	3.7	5.3
N_2 semi-major axis (cm/s)	–	1.2	–
O_1 semi-major axis (cm/s)	–	1.0	–

Offshore distance is the approximate distance for each mooring measured from the coast. Δt and Δz are, respectively, the sampling intervals in time and depth. Average min. depth and average max. depth are respective average centers of the shallowest and deepest depth bins in which currents were accurately measured. Semi-major axis values refer to the semi-major axis of the barotropic tide current ellipse. Because the time-series are shorter at moorings S2 and S1, tidal estimates there are less accurate than at mooring N.

approximately in the along-shore direction near Senigallia. Currents near the direction and magnitude of the mean flow (Fig. 2) occurred frequently throughout the record and were especially frequent during March. Like the mean flow, velocities were largely barotropic with depth. Flow towards the northwest very rarely occurred.

In Fig. 4, currents outside the two-standard-deviation ellipse are drawn with thick lines. Such an ellipse is twice the (linear) size of the usual standard-deviation ellipse (Fig. 2) and encloses over 86% of the vectors from a bi-normal distribution. For the velocities at mooring N, these ellipses enclose an even greater percentage of vectors because the sampling distribution departs from the bi-normal distribution due to an elongated tail in the southeast (along-shore) direction. Most of the anomalous currents as shown in Fig. 4 occurred during a few depth-coherent events in the record. Events occurred in late January, in late February, near April 1st, and as a single or double event in mid April. Each event was characterized by an increase in the intensity of the southeastward along-shore flow throughout the water column. On average, these current bursts persisted for 3.5 days with mean depth-averaged currents of 23 cm/s directed toward 135°. During all four events, depth-averaged currents exceeded 30 cm/s at some time; during the late February and April 1st events, they exceeded 39 cm/s. The maximum depth-averaged current speed of 45 cm/s occurred during the late February event. The temporal variability of the currents remained high during the current bursts.

All three moorings observed the late January current burst. Just before the current burst, the velocity at S1 was toward the west, while at S2 and N the velocity was toward the southeast. During the current burst, all three records had high southeast velocities and coherent structure. Maximum velocities occurred at the inshore moorings, S2 and N. Immediately following the current burst, velocities slowed at moorings S2 and N, while velocities at mooring S1 remained near 12 cm/s and turned toward the south. For the last five days of the S2 and S1 deployments there were two periods of coherent southeastward flow with typical speeds ranging from 8 to 15 cm/s, separated by a period when flow tended to be weaker, less coherent, and more variable in direction.

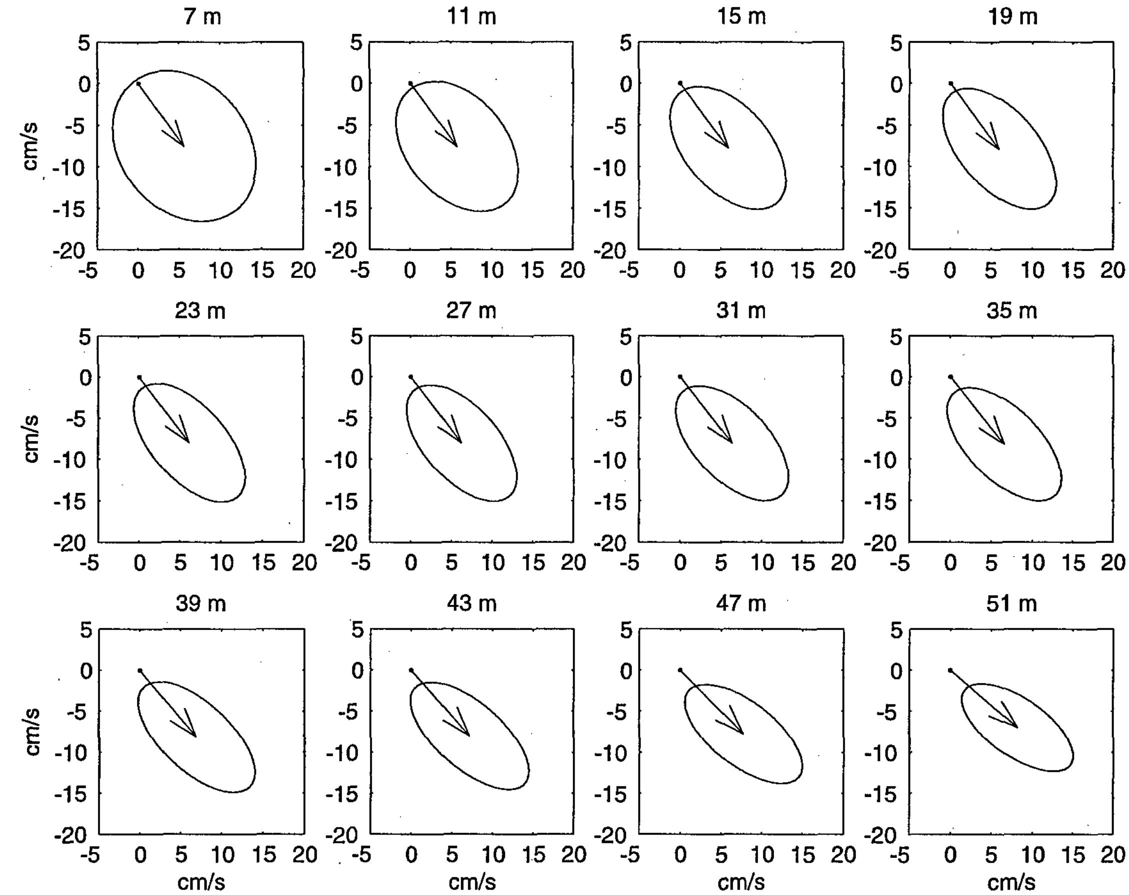

Fig. 2. Mean current vectors and standard-deviation ellipses for odd numbered ADCP depth bins from January 28 through April 30. Tidal velocities were removed prior to this calculation. The depth average current has magnitude 10.4 cm/s directed toward 140°.

2.2. Temperature

The bottom panel of Fig. 4 shows the bottom temperatures recorded by ADCP N. Abrupt drops in temperature at the times of current bursts are immediately apparent. Although barely noticeable during the late January burst, these drops become increasingly pronounced during subsequent bursts. Thus, during the temperature decline from January 29 until March 31, after removing a mean and annual sine wave evaluated from the entire mooring N temperature record, the standard deviation of temperature is only 0.22 °C. In contrast, at the start of the April 1st current burst the temperature plummeted 2.2 °C and from March 31 to April 17 the standard deviation of seasonally de-trended temperature was 0.58 °C. From April 17 through April 30, the comparable, non-seasonal standard deviation was 0.32 °C. The fitted annual variation at mooring N for 2001 has a mean of 14.2 °C, a sinusoidal amplitude of 1.6 °C, and a minimum on March 29. From the fitted 2001 annual variation, the mean wintertime (January 1 through April 30) temperature of the outer WAC is estimated to be 13.0 °C.

At and near the time of the late January current burst all three moorings recorded bottom temperature. During much of this time, highest temperatures were found offshore and lowest temperatures onshore, with S1 temperature often ~0.5 °C higher than that at the other two moorings. S1 temperatures also showed the highest variability with occasional abrupt shifts on the order of 0.5 °C. During the first half of the current

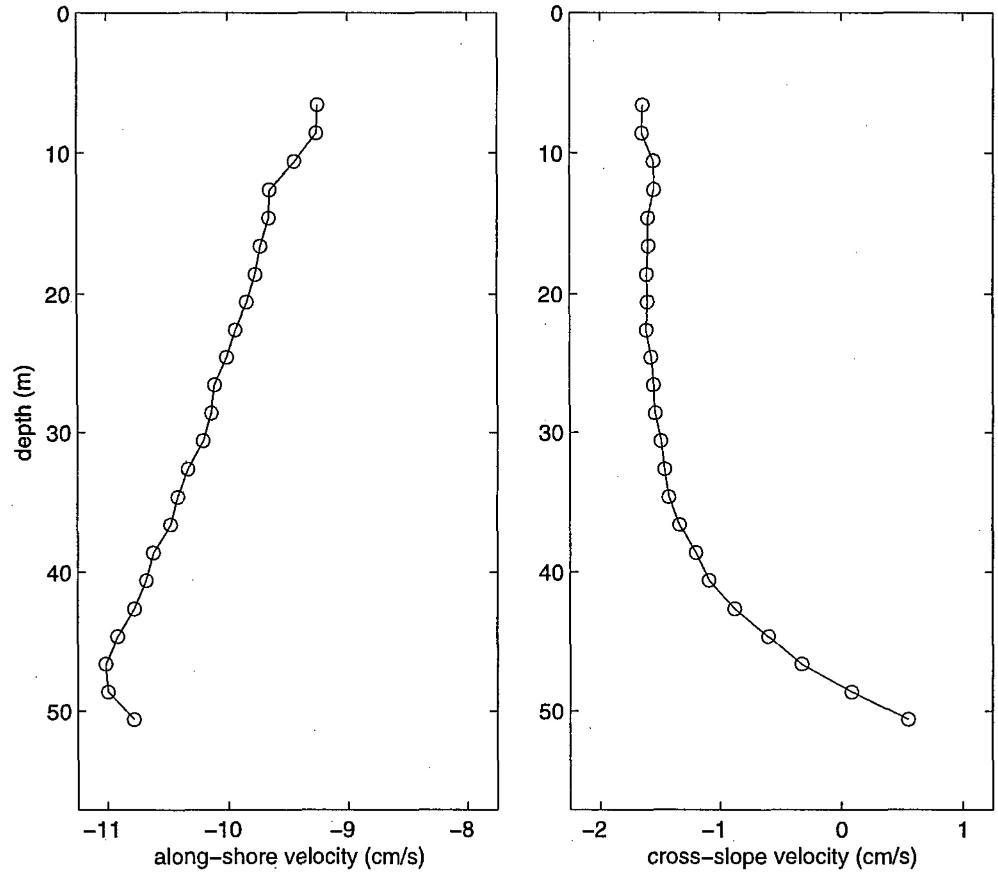

Fig. 3. Mean currents at mooring N. Negative currents in the left panel are directed toward 133°, approximating the along-shore direction near Senigallia (see Fig. 1). Negative currents in the right panel are directed toward 223°, approximating the cross-slope direction toward Senigallia.

burst, mooring S1 temperatures rose to 14.3 °C and then dropped back to pre-burst temperature values near 13.8 °C, mooring N temperatures dropped 0.25 °C to values near 13.55 °C, and mooring S2 temperatures oscillated between low (minimum at 13.3 °C) and high (maximum at 13.9 °C) values. For brief periods during this time frame, the bottom temperatures at S1 and S2 were nearly identical while temperature at the central mooring N was ~0.25 °C degrees colder than at the other sites. During the second half of the current burst, mooring S1 temperatures abruptly dropped 0.25 °C, rose 0.35 °C, and then steadily declined to values near 13.7 °C. At the same time, mooring N temperatures remained relatively steady at values near 13.65 °C and mooring S2 temperatures ranged between 13.35 and 13.6 °C, thus maintaining a high to low temperature difference between offshore and onshore.

2.3. Winds

The Istituto di Scienze Marine – Consiglio Nazionale delle Ricerche (ISMAR-CNR) in Venice maintains instruments on an offshore platform called Acqua Alta in the northern Adriatic (Cavaleri, 2000). Wind speed and direction, air temperature, ocean temperature near the surface (5 m), ocean temperature near the bottom (12 m), and several other parameters were recorded at this platform during the interval that

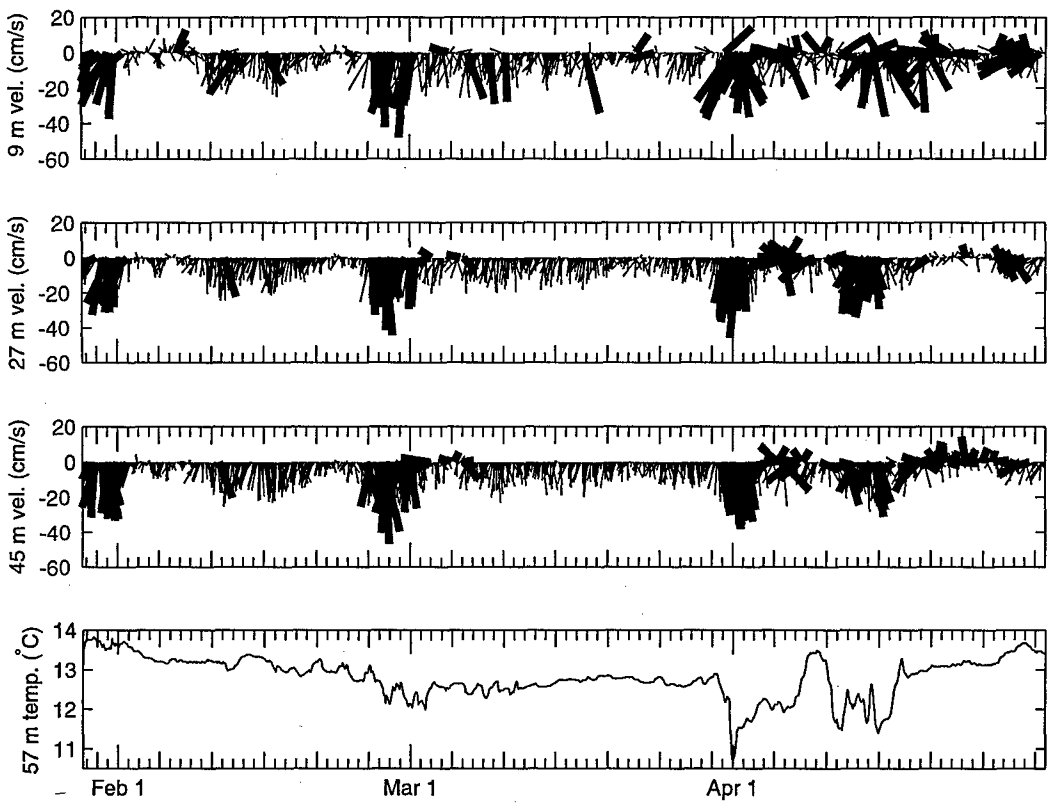

Fig. 4. Observed velocities and temperatures at mooring N from January 28 through April 30. The de-tided velocity data were subsampled every 3 h for visual clarity. The negative y-axis on the velocity panels points toward 133°, approximating the along-shore direction near Senigallia. Velocity vectors lying outside a two-standard-deviation ellipse (see Fig. 2) are drawn as thick lines. Large tick marks denote the start of each month, medium tick marks denote month days that are divisible by five, and small tick marks denote days.

includes the ADCP observations. Fig. 1 shows the position of the platform, 16 km off the coastline of the Venice Lagoon.

Fig. 5 shows the wind vectors recorded at Acqua Alta during the winter period when mooring N was deployed. Wind data were collected at the tower every 10 min; for visual clarity Fig. 5 presents the wind vectors subsampled every 2 h, and rotated so that the positive y-axis is aligned with the principal major axis of variation of the wind time series. This direction is 255°, the general flow direction of bora winds at this location (Zecchetto & Cappa, 2001). Sirocco winds at Acqua Alta are directed in a general northwestward direction (Guymer & Zecchetto, 1993).

Several bora events took place during the winter of 2001. A strong bora (not shown) occurred in mid January before mooring N was deployed. A brief bora occurred in late January, preceding the current burst recorded by all three ADCPs. In mid February, a brief strong wind event occurred. This wind was directed towards 285°, more northerly than the typical bora, and does not seem to be associated with strong current anomalies at mooring N. A bora occurred in late February and another in early March. The stronger of these directly preceded the late February current burst, but no noticeable current burst followed the weaker bora in early March. Two bora events also occurred in late March and mid April, the first having a double peak. The April 1 current burst at mooring N took place during the second peak, the stronger of the two. The second bora occurred at the same time as the mid-April current burst at mooring N. Winds between

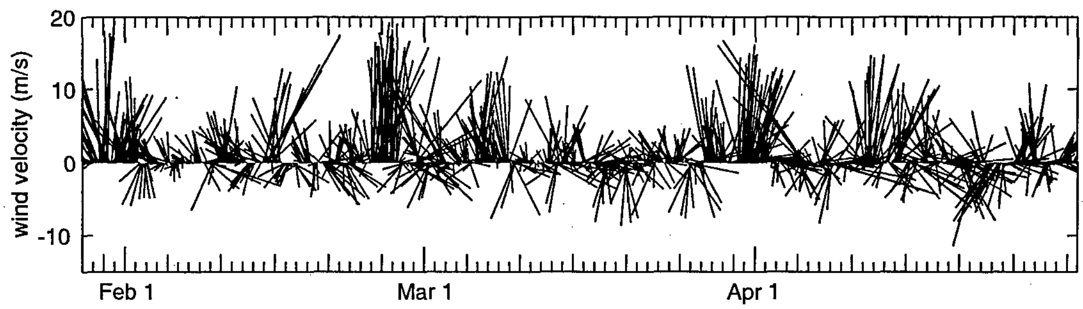

Fig. 5. Observed winds at the Acqua Alta platform near Venice from January 28 through April 30, subsampled every 2 h for visual clarity. The positive y-axis is aligned with the principle axis of variation of the wind time series, 255°, which is also the approximate flow direction of bora winds at this location. Large tick marks denote the start of each month, medium tick marks denote month days that are divisible by five, and small tick marks denote days.

these two bora events were strong and changed directions quickly, blowing first southwestward and then, after a brief lull, in a northward direction.

To examine spatial features of the winds and how they relate to the flow at mooring N, we have used winds from the atmospheric portion of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) applied in a reanalysis mode (Hodur, 1997). The COAMPS atmospheric model is a finite-difference approximation to the fully compressible, non-hydrostatic equations and uses a terrain-following vertical coordinate transformation. A full suite of physical parameterizations is used to represent boundary layer, radiative and moist processes including microphysical quantities (Hodur, 1997). An incremental-update, data-assimilation procedure that enables mesoscale phenomena to be retained in the analysis increment fields is used to initialize the real-data simulations. Initial fields for the model are created from multivariate optimum interpolation analyses of upper-air sounding, surface, commercial aircraft, and satellite data that are quality controlled and blended with the 12-h COAMPS forecast fields. The Navy Operational Global Analysis and Prediction System (NOGAPS) forecast fields are used for lateral boundary conditions. The domain configuration for these reanalysis simulations contains three horizontally-nested computational grids with horizontal grid spacing of 36, 12, and 4 km. The 4-km resolution grid mesh is centered over the Adriatic Sea. The model uses a terrain-following vertical coordinate with 30 vertical levels on a non-uniform vertical grid with an increment of 10 m at the lowest level. Topographic data is based on the US National Imagery and Mapping Agency (NIMA) 100-m horizontal resolution data set that enables key topographic features surrounding the Adriatic to be resolved. At Acqua Alta, COAMPS winds are in rough qualitative agreement with measured winds, but differ in some details.

Figs. 4 and 5 indicate that southeastward along-shore current bursts at mooring N are associated with particular wind events. To investigate this further, normalized cross-covariance functions were calculated for every third COAMPS grid point between the along-shore velocity at 43 m and time series of wind stress from COAMPS. Velocities at 43 m, should be among the least sensitive to direct surface wind effects and bottom friction effects. For positive time delays, τ, and wind angles, θ, the normalized cross-covariance, ρ, is given by:

$$\rho_{vw}(\tau,\theta) = \frac{1}{\sigma_v\sigma_w(\theta)[T-d(\tau)-1]}\sum_{i=1}^{T-d(\tau)}[v(t_i)-\mu_v][w(\theta,t_i+\tau)-\mu_w(\theta)], \tag{1}$$

where $v(t)$ is the along-shore velocity, $w(\theta,t)$ is the component of wind stress in the θ direction, t is time, T is the total number of points in the time series, d is equal to the numerical value of τ in hours, and i is a 1-h indexing variable. σ and μ are the standard deviations and means of the time series to which they pertain. For negative time delays, $\rho_{vw}(\tau, \theta) = \rho_{wv}(-\tau,\theta)$. Cross-covariances were calculated in increments of 5° in direction and 1 h in time. Current velocity data gaps were filled by linear interpolation for the calculations. From these cross-covariances the maximum magnitude was determined over all wind stress orientations and time lags up to ±5 days (Fig. 6). Maximum cross-covariance magnitudes occur in a pattern very similar to bora wind magnitude patterns (Pullen et al., 2003) with high values along the northern Adriatic coast, off Kvarner Bay, and off Ilovik Island (14.5°N, 44.4°E). Peak cross-covariance occurs at the tip of the Istrian Peninsula just outside Kvarner Bay. Fig. 7 shows the wind stress directions associated with the maximum cross-covariance magnitudes presented in Fig. 6. The directions shown in Fig. 7 are associated with negative cross-covariance, i.e., high wind speeds associated with negative (southeast) along-shore currents. In general, these directions are similar to bora wind directions (Zecchetto & Cappa, 2001).

Fig. 8 shows the cross-covariance functions for the tip of the Istrian Peninsula (site of maximum magnitude) and for a site near mooring N. Correlation is higher between the wind stress off the Istrian Peninsula and the mooring N velocities than between the wind stress near mooring N and the mooring N velocities. Peak correlation occurs at a time lag of −1 h for the wind stress near mooring N, but at −14 h for the site of maximum cross-covariance magnitude. Peak cross-covariance off the tip of the Istrian Peninsula and elsewhere are broad with respect to wind stress angles and time lags. In the top panel of Fig. 8 the higher valued contours are tilted, i.e., higher correlations occur for longer time lags with winds directed more toward the east and for shorter time lags with winds directed more toward the southeast. This trend becomes stronger in the cross-covariance functions (not shown) to the northwest of this point, off the west coast of Istria.

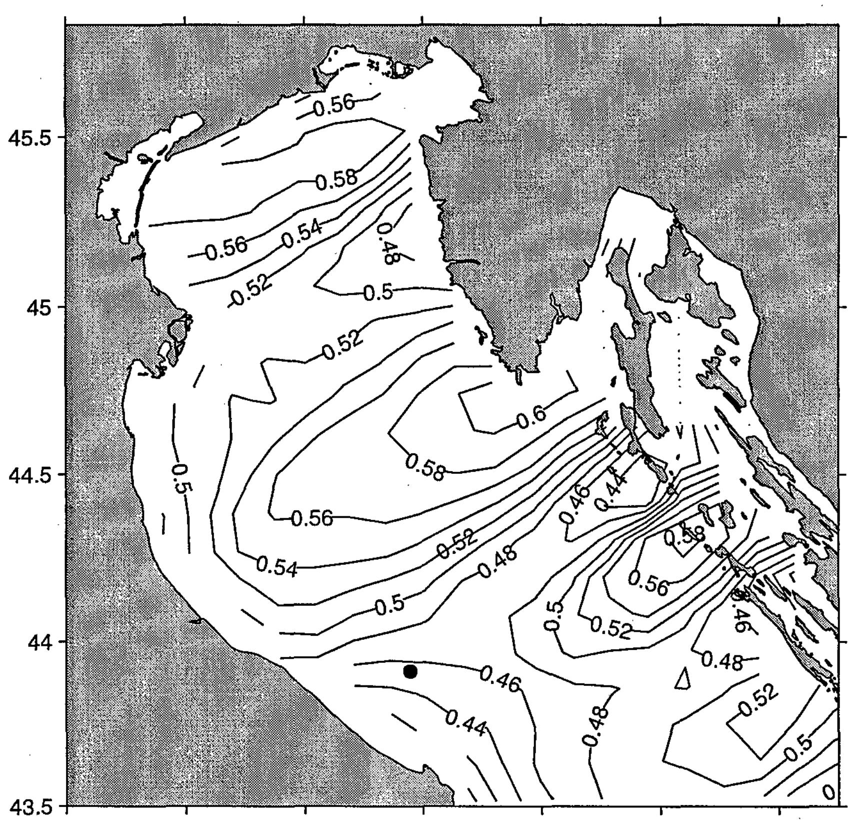

Fig. 6. Maximum cross-covariance magnitudes between along-shore velocity at mooring N and COAMPS wind stress for all wind stress directions and all time lags. The position of mooring N is indicated by a black circle.

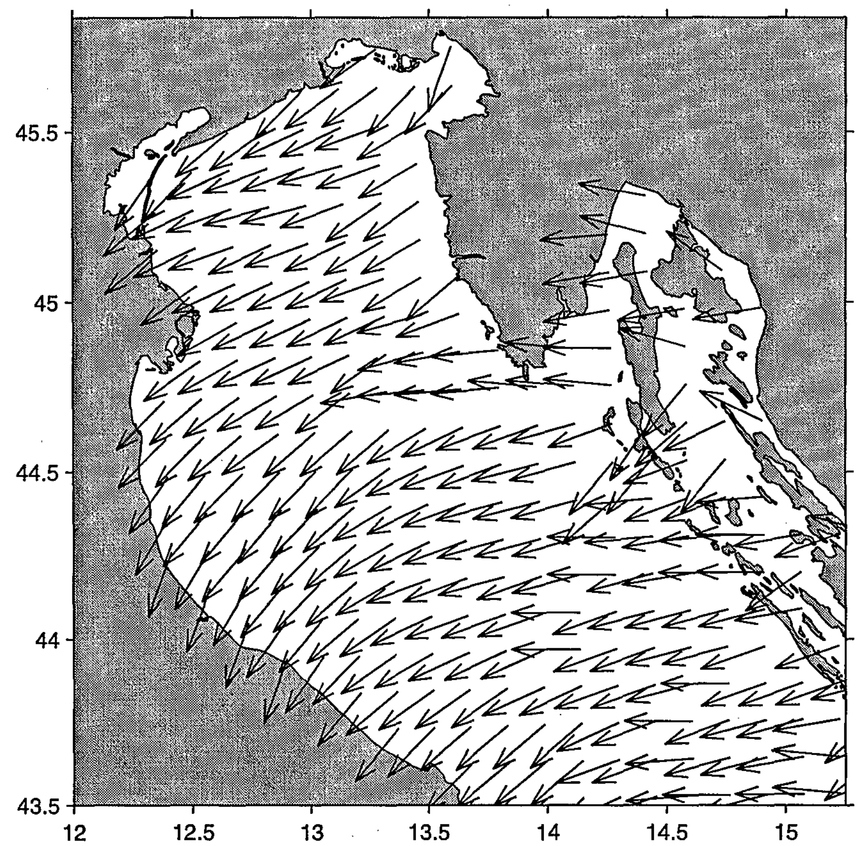

Fig. 7. Equal-length vectors in the direction of wind stress at which maximum cross-covariance magnitude between along-shore velocity at mooring N and COAMPS wind stress occurred for all wind stress directions and all time lags. The directions are associated with negative covariance, i.e., high wind speeds associated with negative (southeast) along-shore currents.

Here, strongest correlation occurs for time lags of −16 h and a wind stress direction of 260°, but a secondary maximum occurs at a time lag of −6 h and 240°. Just to the south of Istria, cross-covariance maxima (not shown) are broad and display the same tilt as in the top panel of Fig. 8, but peak values occur for shorter time lags (~5 h). Cross-covariances (not shown) off Ilovik Island are also tilted and have high values for both shorter and longer time lags. However, between Venice and Trieste, cross-covariance contours (not shown) are barely tilted, and function values peak at time lags of 8–15 h.

3. Discussion

Relatively steady currents were observed at mooring N for much of the winter of 2001. Both bottom frictional forces and direct wind forces are inconsistent with the observed mean current speed increase with depth. Time derivative forces over three months should be small. Therefore the dominant balance for the observed mean currents is most likely geostrophic. Under this assumption, the Coriolis force generated by the mean current of 9.4 cm/s at 7 m depth must be balanced by an onshore pressure-gradient force from a mean surface slope of $\sim 9.7 \times 10^{-7}$ rising toward 233°. For a linear slope, this is equivalent to a 2.7 cm rise from mooring N to the Italian coast ~28 km away. Mean along-shore currents at mooring N

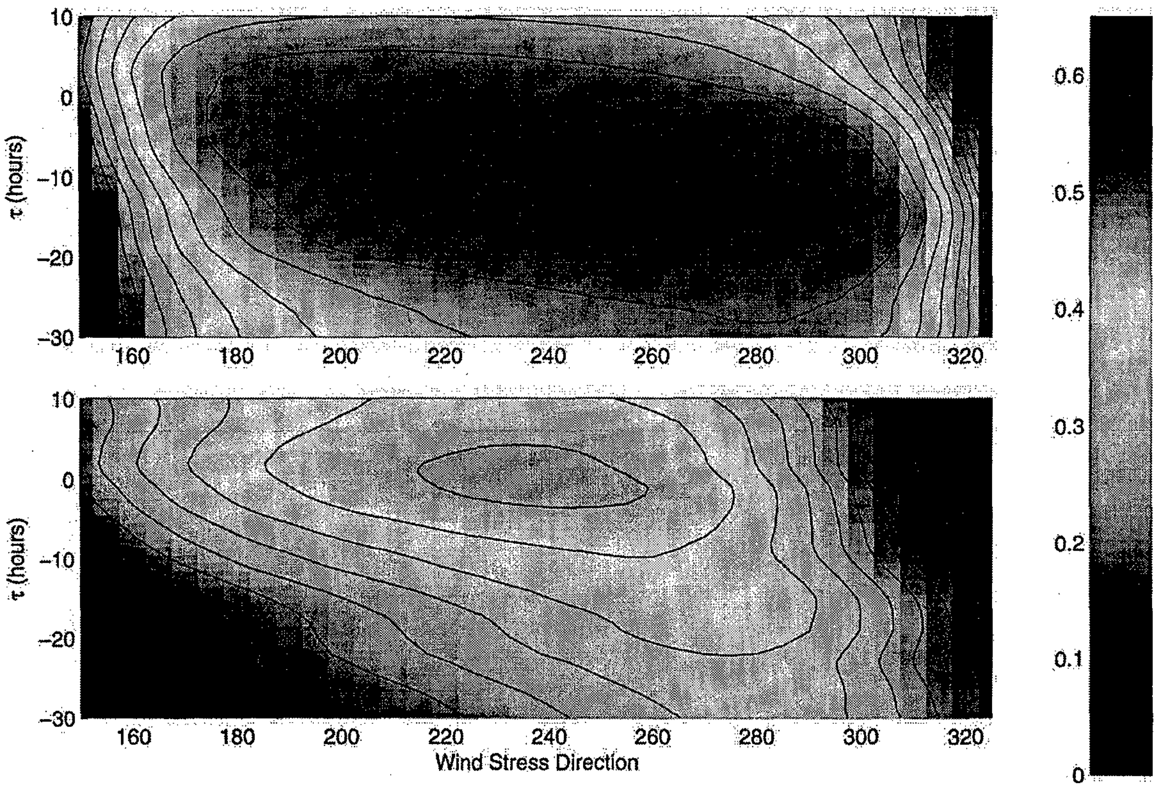

Fig. 8. Cross-covariance function magnitudes between mooring N along-shore velocity at 43 m and COAMPS wind stress. The top panel shows the cross-covariance for the wind stress location with maximum cross-covariance magnitude, i.e., off the tip of the Istrian Peninsula (44.75°N, 13.95°E). The bottom panel shows the cross-covariance for a wind stress location near mooring N (43.96°N, 13.52°E). Colors represent the value of the cross-covariance functions. Contour intervals are 0.05.

are predominantly barotropic, but increase linearly with depth by 1.8 cm/s between 7 and 47 m depth. Such a trend under geostrophic balance implies a depth-independent, cross-slope density gradient of $\sim 4.7\times10^{-6}$ kg/m^4, with denser water lying inshore of mooring N. This small cross-slope gradient could be produced by a ~0.2 °C decrease in temperature or a ~0.06 psu increase in salinity over 10 km, but since both temperature and salinity are known to decrease shoreward, a larger temperature decrease is required to compensate for the decrease in salinity. Above 13 m and below 47 m at mooring N, direct wind forcing and bottom frictional forces may also play their respective roles, but these depth ranges could not be adequately observed by the ADCP.

The mean current veers seaward near the bottom. Mean cross-slope currents are small and relatively depth independent above 35 m, but change below that depth from 1.4 cm/s onshore to 0.6 cm/s offshore, the rate of change increasing rapidly with depth (Fig. 3). Under a geostrophic balance, the observed shear in the cross-slope currents implies a southeastward along-shore density gradient increasing linearly with depth, from 2×10^{-6} kg/m^4 at 34 m to 25×10^{-6} kg/m^4 at 50 m. As an alternative theory, a simple bottom Ekman layer and a depth-independent, cross-slope density gradient were fitted to the observed mean velocity profiles. The best-fit profile had an eddy viscosity of 1.2×10^{-3} m^2/s, producing a boundary-layer thickness of 5 m, but did not agree well with the strong shear observed in the cross-slope current profile. Under the constraints imposed by this simple theory, the fit is poor because the strong veering observed in the cross-slope currents would be accompanied by departures from a linear structure in the along-shore currents, contrary to what was observed. A more realistic theory is needed to explain the cross-slope current structure. Possible approaches to improving the fit between observations and theory include using a three-dimensional density gradient and/or using a more advanced Ekman-layer formulation that accounts for buoyancy and sloping bathymetry effects.

During the winter of 2001, most large departures from the mean flow in the outer WAC occurred as a result of bora winds. Near the time of strong bora events, along-shore currents increased to as much as 30–45 cm/s and lay outside the two-standard-deviation ellipse around the mean current. This result agrees with observational studies of the WAC in the 1980s, which reported a mean flow of 10 cm/s, with wind-driven variability of up to 20–40 cm/s (Cushman-Roisin et al., 2001). Recent numerical model results are also consistent with our observations. Paklar et al. (2001) show strong southeastward surface currents in the vicinity of mooring N, driven by bora winds. The WAC was intensified during bora events in the model of Bergamasco et al. (1999). Data from the three instruments deployed during the late January current burst indicate that bora-driven current bursts can be wider than 9 km. In contrast to the stronger bora events, some weaker bora events during 2001 produced little increase in current. For example, neither the small bora in early March nor the first pulse from the late-March bora immediately precede strong current anomalies at mooring N. The reason for this is unclear. Both of these example bora events are present in the Kvarner Bay COAMPS winds as well as the Acqua Alta Tower winds and therefore are not likely to be dark bora.

Maximum magnitudes of the cross-covariance between COAMPS wind stress and along-shore current has approximately the same spatial pattern (Fig. 6) as the bora itself, with strongest correlations along the northern Adriatic coast, off the southern tip of Istria, and off Ilovik Island. Since bora winds at different locations are correlated to each other, it is expected that if strong bora winds in one region are correlated with currents at mooring N, then strong bora winds in another region will also be correlated with these currents. In the bora impact regions off Kvarner Bay and off Ilovik Island, the cross-covariance functions have broad maxima with highest correlations for southwestward winds with shorter ($\sim$5 h) time lags and for westward winds with longer ($\sim$14 h) time lags (Fig. 8). This suggests that two different wind-forced phenomena may be strongly impacting the outer WAC flow. Peaks in cross-covariances for both shorter and longer time lags occur off the tip of the Istrian Peninsula. The model of Paklar et al. (2001) shows a cyclonic gyre connecting the area off the tip of the Istrian Peninsula with the outer WAC during a bora. Highest correlations and modeled connections with the outer WAC all occurring near the tip of Istria make it plausible that current anomalies observed at mooring N could be generated in that region.

Orlić, Kuzmić, and Vučak (1986) computed correlations between winds and currents measured at the Panon station located on the 25 m isobath midway between Trieste and Venice. They found correlations with no time lag between bora winds and downwind currents. Correlating current data from a buoy deployed off the central Istrian coast and wind measured over land nearby, Kuzmić and Orlić (1987) found small time lags (5–6 h) in upper-level currents. At mooring N, highest correlations between wind stress and southeastward currents occurred for remote winds for both short and long time lags (Fig. 8). A flow trajectory curve connecting the region off the southern tip of Istria (the area of highest correlation) with mooring N would have an arc length of about 130 km. If current anomalies were generated there and traveled to mooring N in 5–14 h, group speeds from 3 to 9 m/s would be required. This is too slow for the barotropic wave speed, 24 m/s, and too fast for advective speeds, 0.5 m/s. A 14-h time lag is comparable to the 17-h inertial period, suggesting the spin-up time of the sea plays a significant role.

Using a hydrological database from 1911 to 1981, Artegiani, Azzolini, and Salusti (1989) found that thick layers of cold (<11.3 °C) and dense ($\sigma \geqslant 29.4$) water historically occur in the northern Adriatic during winter. In March and April, dense water is found further south concentrated along the Italian side of the Adriatic. Dense water was found in a vein along the western Adriatic slope by Artegiani and Salusti (1987) in 1981 and during hydrographic surveys (not shown) taken by the Istituto di Ricerche sulla Pesca Marittima (IRPEM) in 2000 and 2002, but not in a comparable IRPEM survey in 2001. Mooring N recorded bottom temperatures less than 11.3 °C only briefly in the winter of 2001, during the April 1st current burst.

The flow of dense water along the western Adriatic slope in 2001, if it occurred at all, was limited to brief times and/or places. The winter of 2001 was mild; perhaps dense water production in the northern Adriatic did not occur or was very limited. Nevertheless, all bora-induced current pulses were associated with a drop in bottom temperature at mooring N. Temperature drops during the first two bora events were not larger than temperature changes during non-bora times but the strength of these drops increased throughout the winter.

Bottom temperatures at mooring N underwent several abrupt changes between high and low values during the late February and mid-April current bursts, but during the April 1st burst they only dropped and rose a single time. Temperatures also did not oscillate during the late January burst but did oscillate at the neighboring moorings S1 and S2 that were deployed at the time. During temperature peaks at mooring S2, mooring N temperatures were colder than temperatures at either of the other two moorings. This overall picture is consistent with a temperature front in the outer WAC that undergoes lateral movement and occasional eddy shedding during bora events. What we can say with certainty is that some temperature features in the outer WAC are narrower than the 9 km spacing between moorings S1 and S2.

Drifter studies have shown that the waters near Acqua Alta can be part of a cyclonic circulation gyre in the shallow region north of the Po River delta and north of Rovinj, Croatia (Mauri & Poulain, 2001). Two CTD sections taken during this study's deployment cruise show that Acqua Alta waters at times have identical water mass properties with areas within the gyre (January 31) and at times are colder and less saline (February 9). Artegiani et al. (1997b) show that in the winter-mean conditions Acqua Alta water is colder and less saline than other areas in the gyre. Fig. 9 shows the 5 and 12 m ocean temperatures measured at Acqua Alta and the 57 m ocean temperature measured at mooring N. Until April 1st, temperatures at Acqua Alta were much colder than temperatures at mooring N. CTD casts taken near Acqua Alta on January 31 and on February 9 had maximum salinity of 37.3 psu. On February 9, when sea surface temperatures were below 9 °C, surface salinities were below 33.5 psu. In both casts the density was too low to qualify as NAdDW.

Before April 1st, the large difference in temperature between mooring N and Acqua Alta suggests that waters in the north were not circulating along the western Adriatic slope but were instead isolated from the mean circulation at mooring N. After mid-March, temperatures at the shallow Acqua Alta site warmed, reaching values above the minimum temperatures observed at mooring N during the April bora events. These pulses of cold water have the same temperature values as the waters at Acqua Alta from days or weeks earlier. Bora induced advection of waters connect mooring N to a range of surrounding waters, but advection speeds are too slow to directly connect Acqua Alta to mooring N over the limited duration of a bora. Therefore, if far northern Adriatic waters were the source of the cold pulses, then cold water formed in late March would have to be advected to a region close to mooring N while being at least partially insulated from the warming that was observed at Acqua Alta. A change in the circulation pattern forced by bora winds could then open a connection between these waters and the outer WAC.

During winter, the Po River is a source of fresh, cold water to the Adriatic and its discharge was at a seasonal high during the late-March bora. As shown by Kourafalou (1999), bora winds favor trapping of southeastward-flowing Po water against the coast. Therefore, it is unlikely that fresh Po water during the late March bora extended to the bottom as far offshore as mooring N to produce the cold temperatures measured there. However, the following scenario suggested by Zore-Armanda and Gačić (1987) provides an alternate pathway for cold Po water to reach mooring N. During bora events, Po River water is advected toward Istria by a bora-induced, double-gyre current system. Near the Istrian coast, a portion of this cold, fresh water turns south and meets the northward-flowing EAC, forming a front. Mixing and convection along this front could possibly produce NAdDW. If this occurred, the area southwest of Kvarner Bay could be a formation site for the briefly observed cold (and possibly dense) water at mooring N. Besides far northern waters and Po River waters other sources could possibly be responsible for the observed cold water and cannot be excluded by these limited observations.

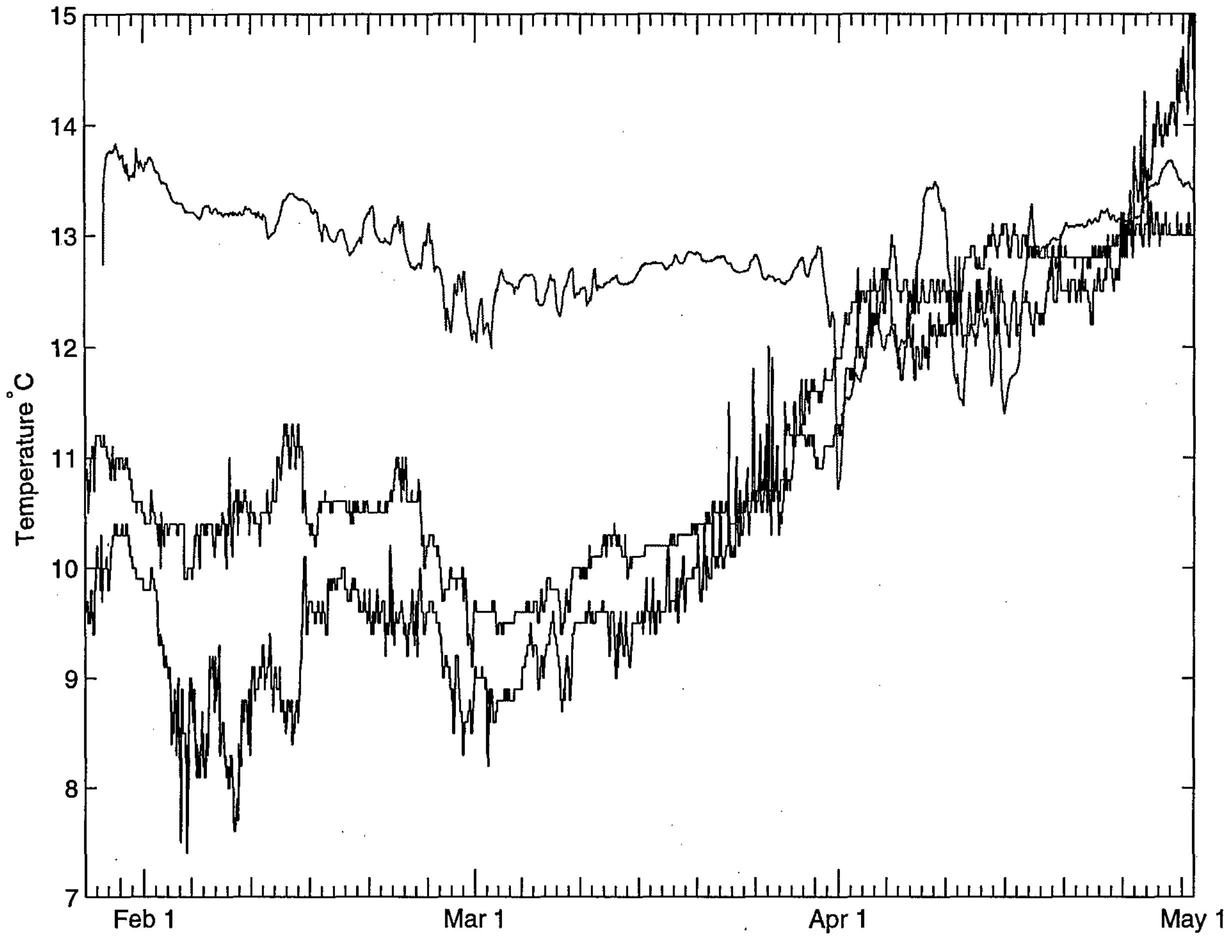

Fig. 9. Observed temperatures at the Acqua Alta platform near Venice at 5 m (black) and 12 m (blue) depth and the bottom temperature (red) at mooring N. The bottom depth at Acqua Alta is 19 m. Large tick marks denote the start of each month, medium tick marks denote month days that are divisible by five, and small tick marks denote days.

4. Conclusions

During the winter of 2001, the outer portion of the WAC along the western Adriatic slope near Senigallia had a mean depth-averaged current of 10.4 cm/s directed toward 140°. The mean current was highly barotropic, most likely associated with a mean surface slope toward shore. Mean along-shore currents increased slightly with depth, consistent with a hypothesized depth-independent, cross-slope mean density gradient.

Variability in the outer WAC along the western Adriatic slope was also primarily barotropic and in the along-shore direction. Southeastward currents greatly increased (exceeding 30 cm/s) following four bora events that occurred between January 28 and May 1st. Following the first of these, currents were enhanced over a region greater than 9 km wide. Smaller bora events did not greatly enhance the southeastward currents. The cross-covariance function between COAMPS wind stress and the along-shore currents at mooring N is stronger where the bora itself is stronger. That is, correlation was higher for wind stress just outside Kvarner Bay than for wind stress over the outer WAC. This suggests some connection between these sites during bora events. The bora-driven, double-gyre system that has been modeled and partially measured by others would produce such a connection.

During the winter of 2001, cold water was not observed along the bottom of the western Adriatic slope as it had been in previous winters. One exception to this was a brief pulse of cold water in the bora-driven April 1st current burst. A mild winter may have limited NAdDW production. Bottom temperature drops occurred during bora events but were very small before April 1st. Oscillating temperatures in the WAC during bora events suggest that complex frontal structures may have been present there.

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